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Magnet FAQs

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The World's Premier Forum on Magnetic Applications, Technologies & Materials

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Questions

- **Permanent magnet key figures of merit**
- Holding force of a magnet
- Temperature capabilities of magnets
- When does permeance coefficient matter?
- Magnetic domains versus particles
- Raw material prices versus magnet selling price
- Magnet R&D: are we due for a blockbuster?

Each of us has questions about magnetism and magnetic materials. Here are a few questions and answers about magnets as used in motors and sensors, magnets for very low or very high temperatures, differences between a magnetic domain and a magnet particle, raw material cost and why the prices change, will there be enough raw materials, what is the size of the magnet industry, how to calculate the holding force of a magnet, what is permeance coefficient and why it matters and more.

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What makes a magnet *good*?

- Flux density (Br, Residual Induction)
- Energy Product (BHmax)
- Resistance to demagnetization (Hcj)
- Usable temperature range
- Change in magnetization with temperature (RTC)
- Demagnetization (2^{nd} quadrant) curve shape
- Recoil permeability (slightly greater than 1)
- Corrosion resistance (water, salts, gases)
- Physical strength
- Electrical resistivity
- Magnetizing field requirement
- Available sizes, shapes, and manufacturability

Specific requirements depend upon the application

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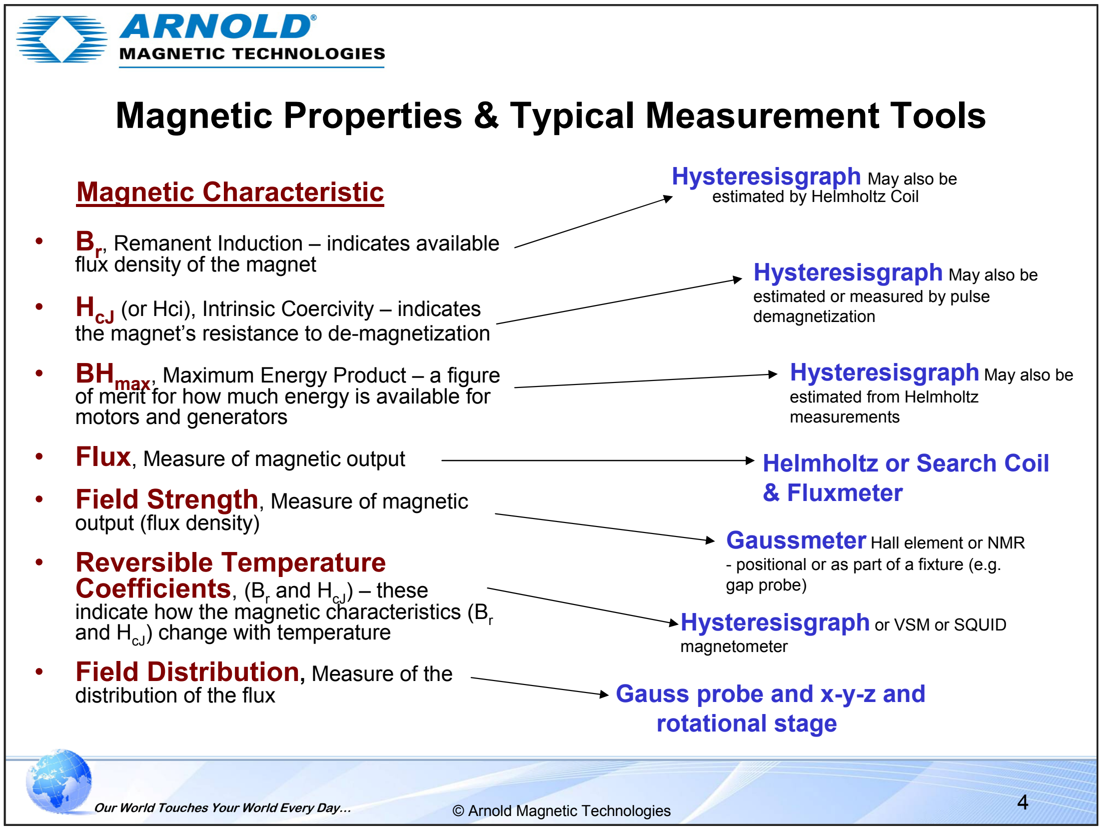
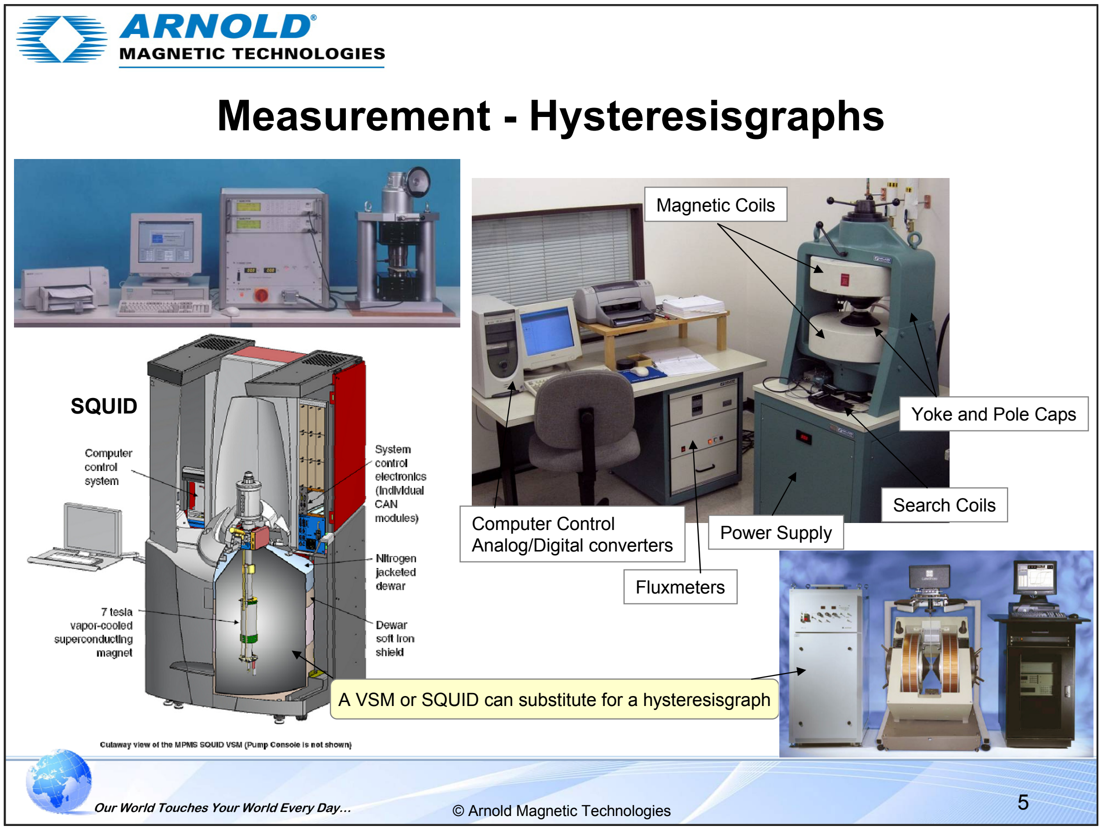
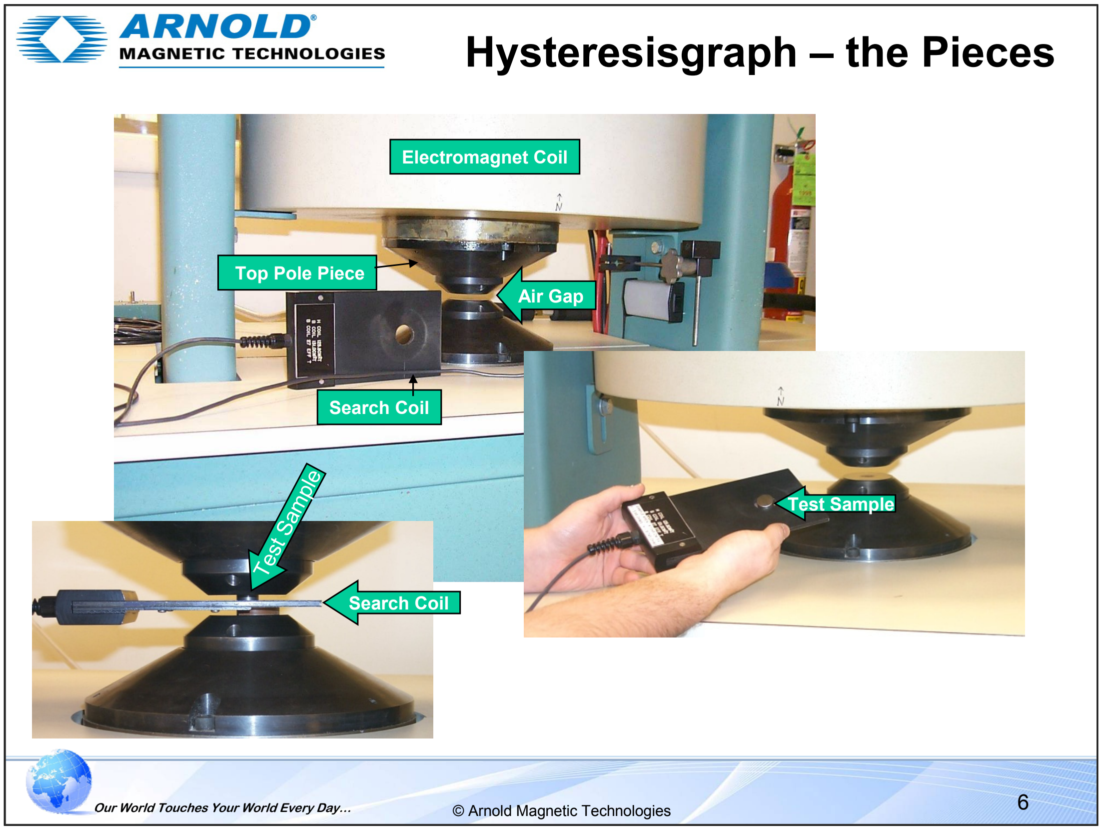
- For each application a subset of these characteristics will determine how well it is suited to the application.
- All of these should be considered by both the magnet manufacturer and the magnet user.



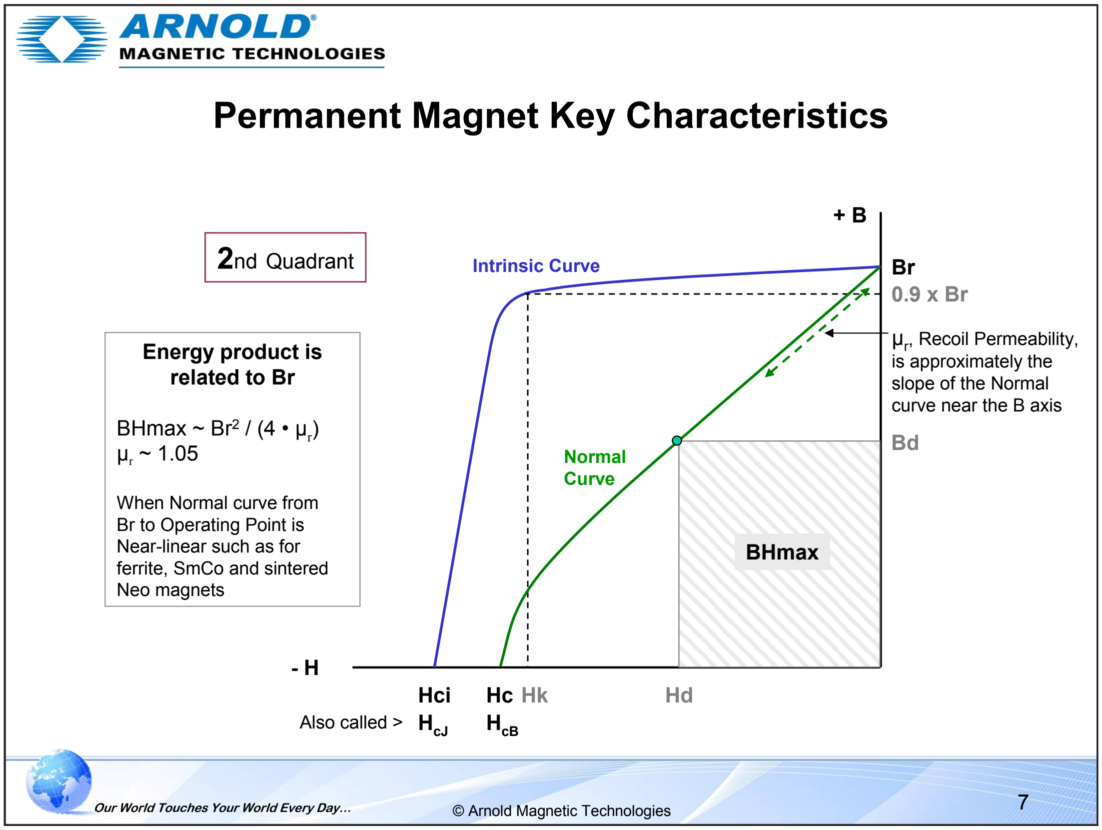
- These figures of merit are used to gauge magnetic "quality" and therefore require measurement at one or more points in the supply chain.
- A device that measures magnetic fields is called a magnetometer.
- The most common type of magnetometer is the hysteresisgraph.
- Other types of magnetometers are the VSM (vibrating sample magnetometer) and SQUID (semi-conducting quantum interference device).
- Other magnetic field measuring equipment includes gaussmeters, fluxmeters, fluxgate magnetometers, NMR (nuclear magnetic resonance) gaussmeters, and combinations of these with coils and sensors.



- The most common equipment for measuring intrinsic magnetic properties is the hysteresisgraph (a.k.a. permeameter).
- The measurement is made in closed magnetic circuit and requires a “regular” geometry where the magnet’s poles are flat, parallel and flush with the faces of the pole caps in the hysteresisgraph.
- The use of a Temperature Stage in a hysteresisgraph allows properties to be measured at lower and at higher temperatures. Arnold, for example, can measure properties in a hysteresisgraph between -40 and 300 ºC.
- A VSM can use environmental chambers into which the open circuit magnet is inserted for testing at temperatures ranging from near zero Kelvin to 1000 °C.



- The hysteresisgraph provides a complete magnetic circuit with pole pieces that adjust to close the gap with the sample in position.
- A power supply provides current to energize coils producing a large magnetic field. This 10” system can produce 34,000 oersteds in a 0.25” (6.4 mm) gap.
- The “search coil” is typically constructed with 2, 3 or more coils around the magnet opening.
- The “B” coil is constructed closest to and in a closed loop around the opening (and magnet).
  - o It measures the B output (induction)
- “H” coil is added outside the “B” coil, around the opening, but does not “close the loop” around the magnet
  - o It measures only the H output
- “H” compensating coil is similar to the “H” coil but is electrically connected to the “B” coil in reverse
  - o Subtracts the H field from the “B” coil output providing B-H (intrinsic induction).
- Electronics process the analog information from the sensors and provide a graphical as well as digital data output for presentation and analysis.



- For permanent magnets we deal most often with just the second quadrant.
- Most of the key figures of merit for permanent magnet materials are indicated on the chart.
- The maximum energy product can be estimated as shown here from just the Br.
- Conversely, the Br can be estimated when the maximum energy product is known.
- As shown, this material would be considered a straight line (Normal curve) or square loop (Intrinsic curve) material since the Normal curve is straight to the maximum energy point.

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- Temperature capabilities of magnets
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Holding Force

Affected by:

- Quality of the magnet-steel interface
  - Flatness and uniformity of the surfaces
  - Roughness of the surfaces
  - Surface coating or gap-creators
- Rigidity during pull-off
  - Pull-away at 90° to the plane of the interface
  - Both materials remain rigid under stress to prevent “peel away”
- Localized saturation of the steel
- Non-uniformity of the magnet or assembly creates non-uniform flux and holding force distribution

Most calculations overstate the actual holding force

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- The closer to the substrate (steel) the greater the holding force of a magnet or magnet assembly. As the magnet moves away from the steel, the pull is reduced.
- If the steel is painted or coated or covered with a non-magnetic material, this forms a gap which reduces the holding force. A rough surface also reduces the holding force.
- A refrigerator magnet is usually flexible and easy to remove from the refrigerator by peeling it away from the steel by lifting a corner or edge to break the magnetic attraction. Similarly, if a rigid magnet is attached to flexible steel, the steel can more easily peel away from the magnet.
- It is tempting to increase holding force by increasing the strength of the magnet. But when a strong magnet is attached to a thin sheet of steel, it is likely to result in the steel becoming “saturated”. Once the steel is saturated very little additional holding force can be expected.
- If the magnet or steel is irregular – has stronger and weaker areas, the weaker region can pull away first thus causing lower holding strength than might be expected.
- Because of these and other variations, Arnold avoids offering simple formula for calculating holding force and encourages FEA followed by thorough testing of the design.

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Holding (Breakaway) Force

$$F = \frac{A \cdot B^2}{2 \cdot C_4}$$

	SI	CGS
F	Newtons	Dynes
A	m^2	cm^2
B	Tesla	Gauss
C_4	1	4

B.D. Cullity and C.D. Graham, Introduction to Magnetic Materials, 2nd ed., IEEE Press, 2009, p.501-2

$$F = k \cdot A \cdot B^2$$

	English
F	Pounds (force)
k	0.577
B	kG
A	in^2

B is induction at the contact point of the magnet assembly and the substrate
k is a shape and contact coefficient

Rollin J. Parker, Advances in Permanent Magnetism, John Wiley & Sons, Inc., 1990, p.186-9

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- But in the event you wish to know...
- These are two versions of the same formula for holding force.
- "B" is the induction, in gauss (or Tesla), at the contact point between the magnet or magnetic assembly and the substrate (steel).
- "A" is the cross-sectional area of contact between magnet (or magnetic assembly) and the steel.
- C_4 and k are constants.

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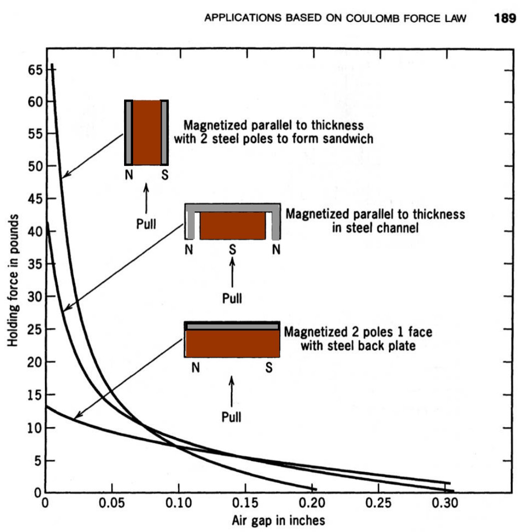
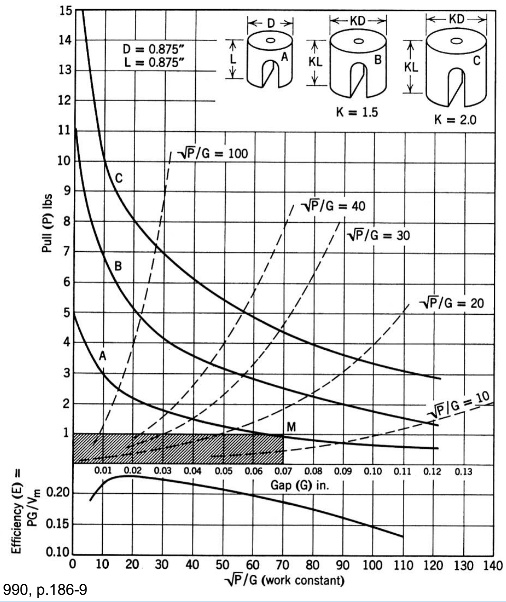
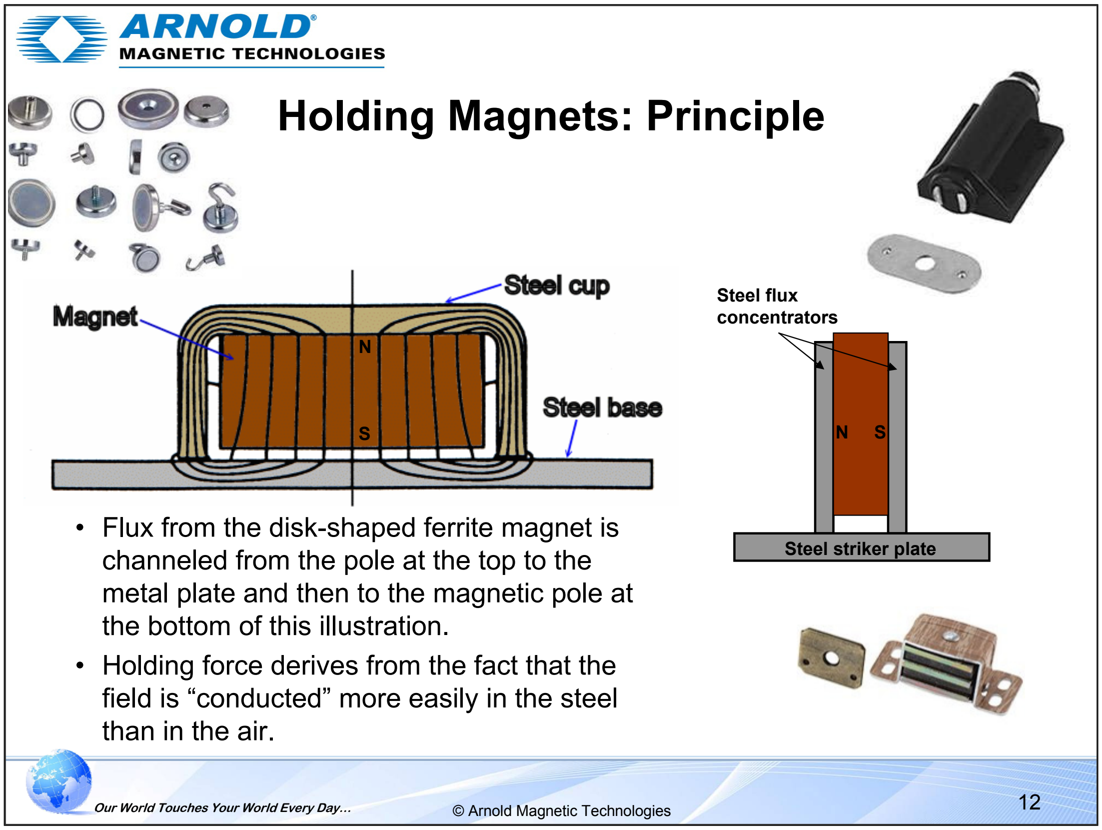
Holding Force for Magnets & Assemblies



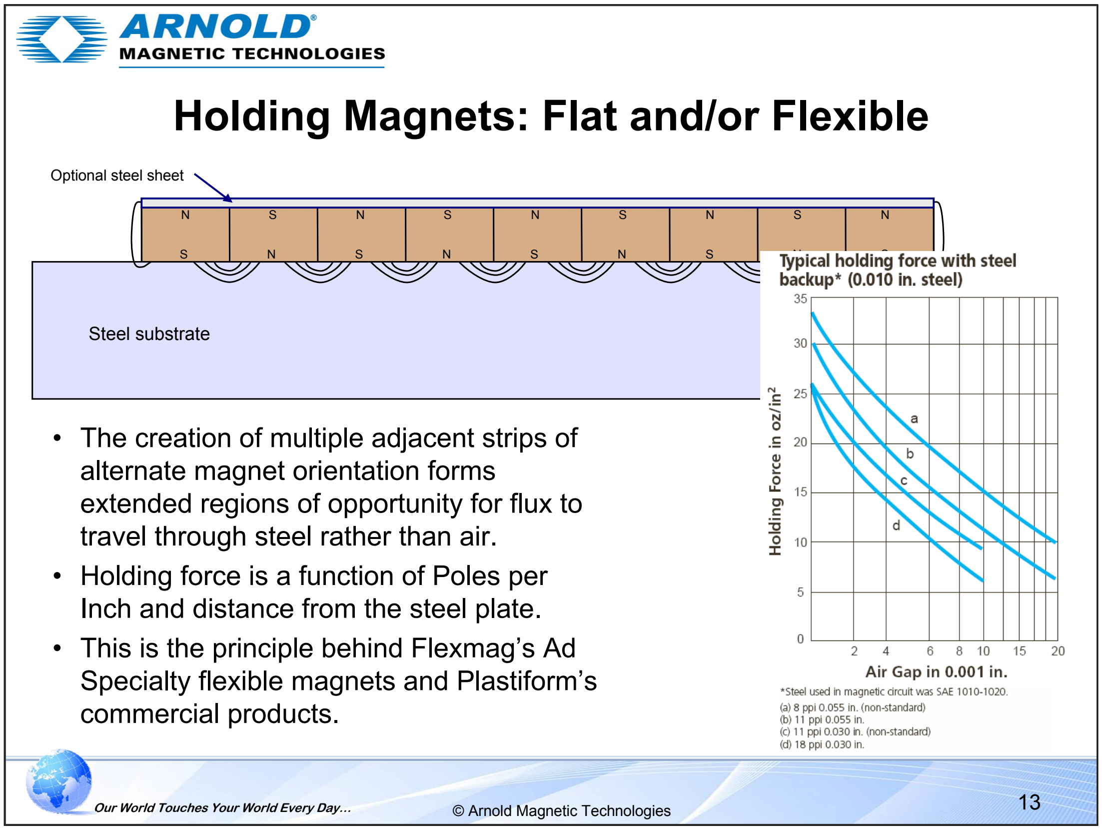


Rollin J. Parker, Advances in Permanent Magnetism, John Wiley & Sons, Inc., 1990, p.186-9

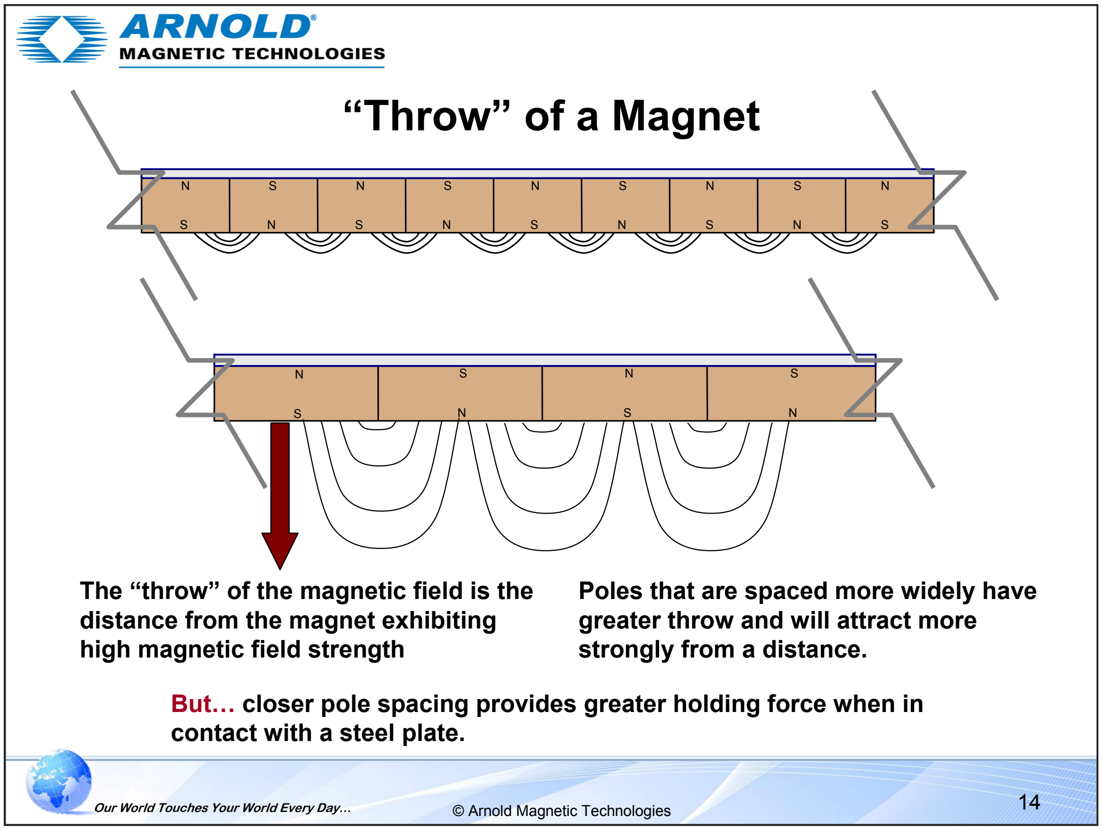
- Because of the complications associated with holding force and because pull at a distance is so often useful, it is more common to find charts showing attractive force as a function of gap between magnet and steel.
- In a design application, the engineering group might be well-advised to generate such a chart for the application and then design a margin of safety by testing imperfect assemblages.



- These illustrations exemplify two types of holding/latching devices.
- The top left illustration is of a cross-section of a "pot magnet."
- Magnets of modest strength can hold with great force when the field is concentrated in this manner.
- The holding force diminishes rapidly as the steel plate is separated from the magnet assembly and holding force is greatly affected by the flatness of the steel plate – the fit between pot magnet and substrate.
- If the steel plate is too thin to carry all the flux, the holding force will also be diminished.
- These assemblies often include a hole in the center of the top for fastening attachments and they use a doughnut-shaped magnet.
- Applications include roof-mount antennas for cars.
- Devices based on rectangular shaped magnets are common for use in cabinet latches.
- The magnet is protected from chipping by being recessed from the contact.



- Flexible ferrite magnets are commonly used in advertising such as refrigerator magnets and are produced in various thickness and pole spacing (see next slides).



- In these illustrations, the flexible magnet has a steel backing to assist the magnetic return path and raise the holding strength of the magnet.
- As one moves away from the surface of a magnet assemblage such as here, the strength of the magnetic field diminishes.
- When the poles are spaced close together the field drops off quickly (top illustration). Conversely, when they are spaced further apart, the field is stronger at large distances from the magnet surface (bottom illustration).
- The top magnet here has superior holding force when directly in contact with steel. The bottom magnet has greater holding power as the gap between magnet and steel increases.
- The overall holding strength is a function of many things among which is the total length of the lines representing the joint (neutral zone) between north and south poles. Each of these joints contributes to the holding force.

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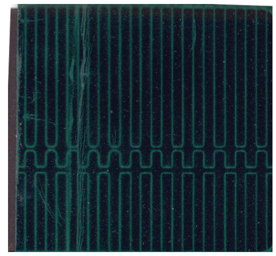
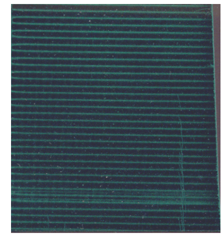
Holding Force of Flexible Magnets

Using magnet viewing paper, we can see the magnetic pole structure.

The light colored lines represent the neutral zone between north and south poles.





www.magne-rite.com

- These refrigerator magnets are made from extruded or calendered ferrite in either a polyethylene or rubber matrix.
- Magnetic poles are impressed on the material to form continuous stripes of north and south pole regions.
- The holding force is created by the interaction of these adjacent poles and is proportional to the total length of the lines formed by the poles.
- The magnet with closer pole spacing (on the right) may have greater holding force due to more lines per inch, thus greater total line length between poles, but the magnet on the left (above Arnold) will have greater throw and be better at holding up more sheets of paper on the refrigerator.
- Green magnetic viewing film shows the neutral plane between poles as a light colored line.

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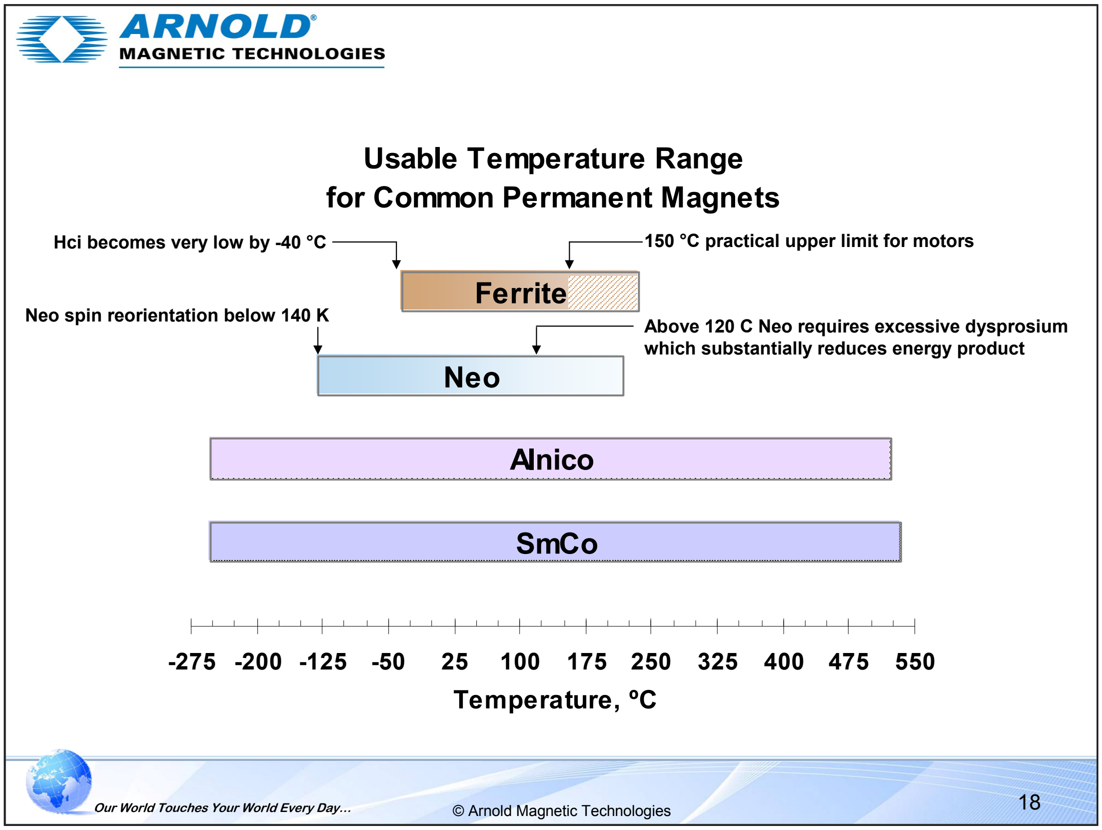
Temperature Ratings of Magnets

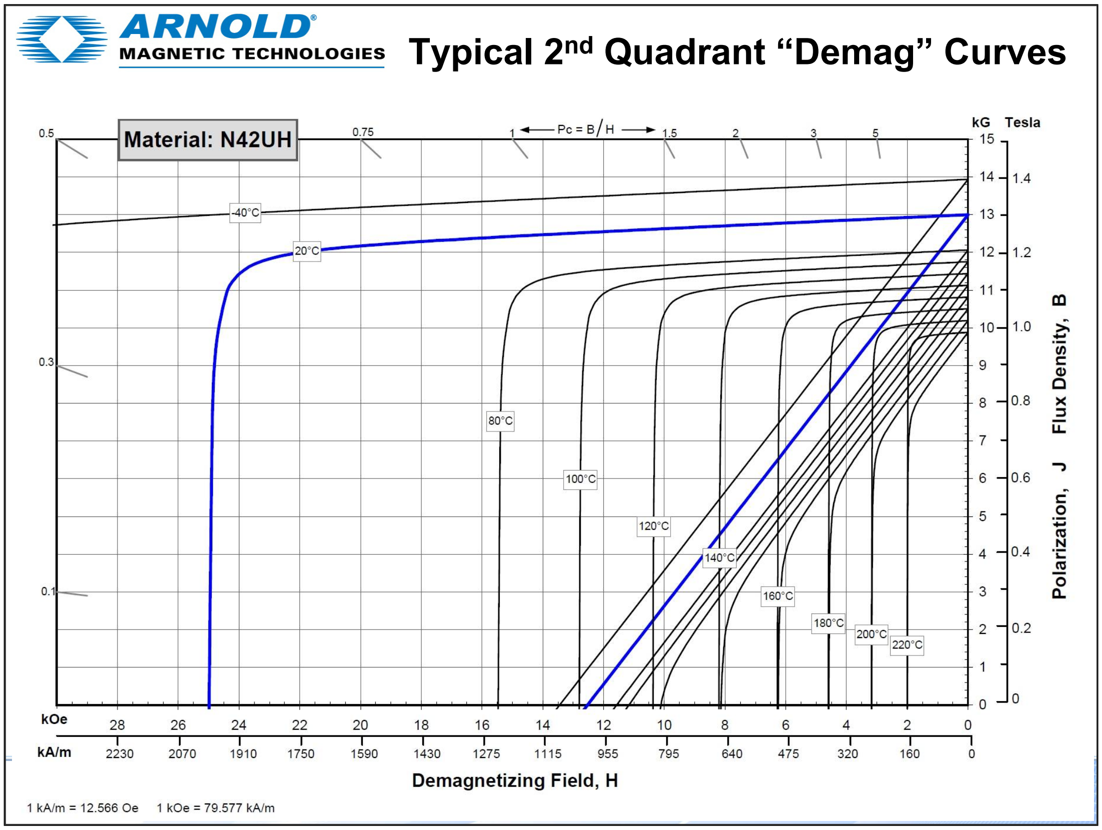
Maximum (and minimum) usable temperatures are determined by:

- Curie (Tc) and Neel (Tn) Temperatures
  - The temperature above which a ferromagnet (Tc) or ferrimagnet (and antiferromagnet) (Tn) becomes paramagnetic; domains realign randomly
- Decrease of Intrinsic Coercivity (and Hk) to such a low value as to be insufficient to withstand demagnetization
- Excessive decrease in flux output due to temperature change
  - Example: Ferrite loses ~25% of flux output going from 20 to 150 °C
- Spin re-orientation
  - Example: Neo below 140 K)
- Decomposition of the magnetic phase
  - Example: SmFeN >450 °C

- The maximum (or minimum) use temperature of a magnet depends on at least these issues.



- A key characteristic in selecting the best magnet is the temperature range of the application.
- We note here that both Neo and ferrite magnets have a more limited useful temperature range.
- Neo is not naturally a high temperature magnet material - we try to make it work at high temperatures by substituting dysprosium for some of the neodymium.
- Ferrite can be theoretically used to over 350 ºC. However, even by 150 ºC, it loses 25% of its flux output and so that is a practical limit for motor applications.



- This is a typical manufacturers chart of second quadrant curves as a function of temperature.
- N42UH is rated to 180 °C, but I've shown performance to 220 °C to exemplify the diminishing Hci.

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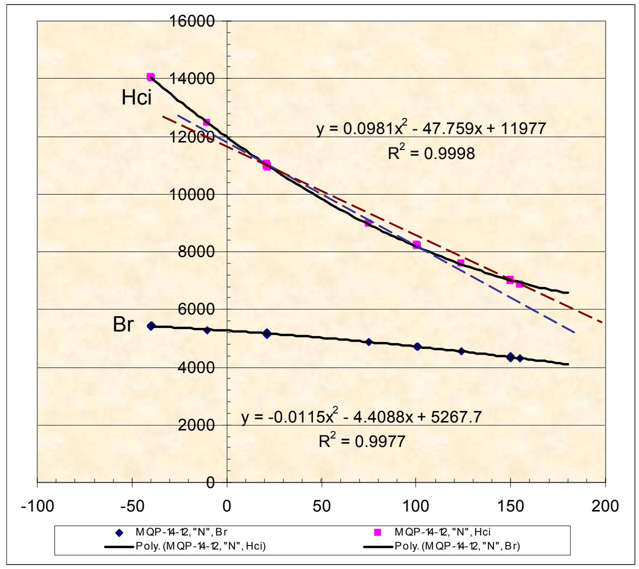
Reversible Temperature Coefficients

- Setting the temperature range over which Beta is calculated is important as can be demonstrated by this illustration.
- The Reversible Temperature Coefficient decreases as the range is expanded from 20 - 100 ºC to 20 - 150 ºC as indicated by the slope of the red dashed line versus the indigo line.
- The actual Beta's are:
  - 20 to 100: -0.325% per ºC
  - 20 to 150: -0.281% per ºC



Material is injection molded MQP-14-12 in PPS

- We quantify the change in magnetic output with changing temperatures as the reversible temperature coefficients of induction and coercivity variously referred to as RTC (reversible temperature coefficient) of Br or Hci, alpha (RTC Br), beta (RTC Hci), or as in Europe, alpha Br and alpha Hcj. Very confusing, so let's just use "RTC".
- One method utilized to calculate RTC with accuracy is to make numerous measurements, on multiple magnets where possible, and to plot the data.
- A regression analysis of the data provides the ability to calculate change in output between any two temperatures within the tested range – and with minor risk, extrapolated outside the tested range.
- One can see from this illustration how the same magnet can be seen to have two (or more) reversible temperature coefficients of coercivity by merely adjusting the temperature range over which they are calculated and specified.

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Permeance Coefficient
and When Does it Matter

- A magnetic circuit comprises a magnetic circuit (magnet and a soft magnetic material such as iron to guide the flux) and an air gap.
- Within every permanent magnet is a demagnetizing stress which is a function of the material and the geometry of the magnet in the magnetic circuit.
- This stress determines what we call a magnet’s permeance coefficient
- It is often calculated
  - It is the ratio of the length of a magnetic circuit to its air gap
  - Also called the operating slope or B/H
  - Intersection of the operating slope line with the normal curve produces the Operating Point
  - Often it is calculated with only the magnet present

J.M.D. Coey, Magnetism and Magnetic Materials, p.466-7

- A magnet’s permeance coefficient is also called its operating slope or its B/H.
- It is strictly a function of the geometry of the magnetic circuit.

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How to Calculate the Permeance Coefficient

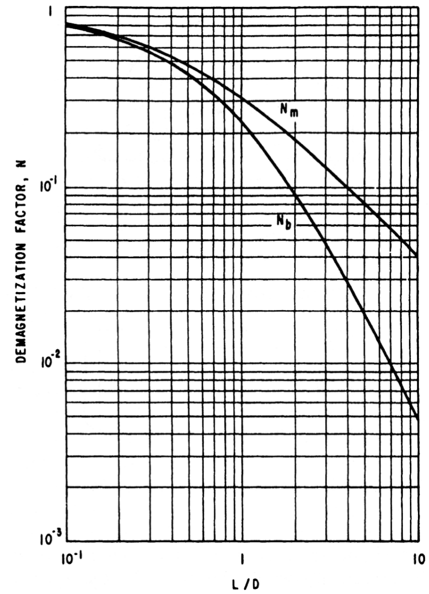
- B/H is related to N (Nb or Nm)

$$\frac{B_d}{\mu_0 H_d} = 1 - \frac{1}{N}$$

- Nb = Ballistic Demagnetizing Factor
  (S. Evershed, J. Inst Elect. Engrs., Pt. I, 58, 780 (1920)
- Nm = Magnetometric Demagnetizing Factor
  (R.I. Joseph, Ballistic demagnetization factors in uniformly magnetized cylinders, J. App;. Phys. 37 (1966) 4639)
- FEMM

$$N = \frac{4}{4 + 9\ (l/d)}$$

(D. Meeker, www.femm.info/Archives/misc/BarMagnet.pdf)



R.J. Parker, Advances in Permanent Magnetism, J. Wiley & Sons, 1990, p.24

- Going back to 1920, Evershed calculated a quantity called the ballistic demagnetizing factor. It’s related to the permeance coefficient by the equation shown.
- Evershed’s value of N is referred to as the ballistic demagnetizing factor, Nb.
- With the discovery and production of ferrite magnets, R. I. Joseph calculated a magnetometric demagnetizing factor, Nm.
- While working on developing FEMM, David Meeker came up with a very simple formula relating N to the length-to-diameter ratio of a magnet.

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Comparison of Nb, Nm and Meeker Pc

Magnet#	Description	Magnetic Length in	Diameter in	L/D	Pc Bd/Hd	Pc Joseph	Pc Meeker	Pc Evershed
1	SmCo	0.7525	0.3755	2.00	9.45	4.50	4.50	8.90
2	Neo	0.3935	0.7855	0.50	1.29	1.11	1.13	1.41
3	Neo stacked - 1	0.3757	0.2525	1.49	6.18	3.32	3.36	5.43
4	Neo stacked - 2	0.7514	0.2525	2.98	13.3	6.8	6.7	15.7
5	Neo stacked - 4	1.5028	0.2525	5.95	28.9	13.8	13.5	42.0
6	Neo stacked - 6	2.2541	0.2525	8.93	50.3	20.7	20.2	78.0

Bd/Hd is calculated from measurements

Joseph = Pc calculated from the Magnetometric demagnetizing factor (1965-66)

Meeker = Pc calculated from the demag factor using David Meeker's arithmetic formula

Evershed = spherical pole model the formula for which is widely published including in Parker & Studders

Additional references by Benz & Martin, Du-Xing Chen, E. Pardo, J. A. Brug, R. B. Goldfarb, A. Sanchez, M. Kobayashi, A. Aharoni and others

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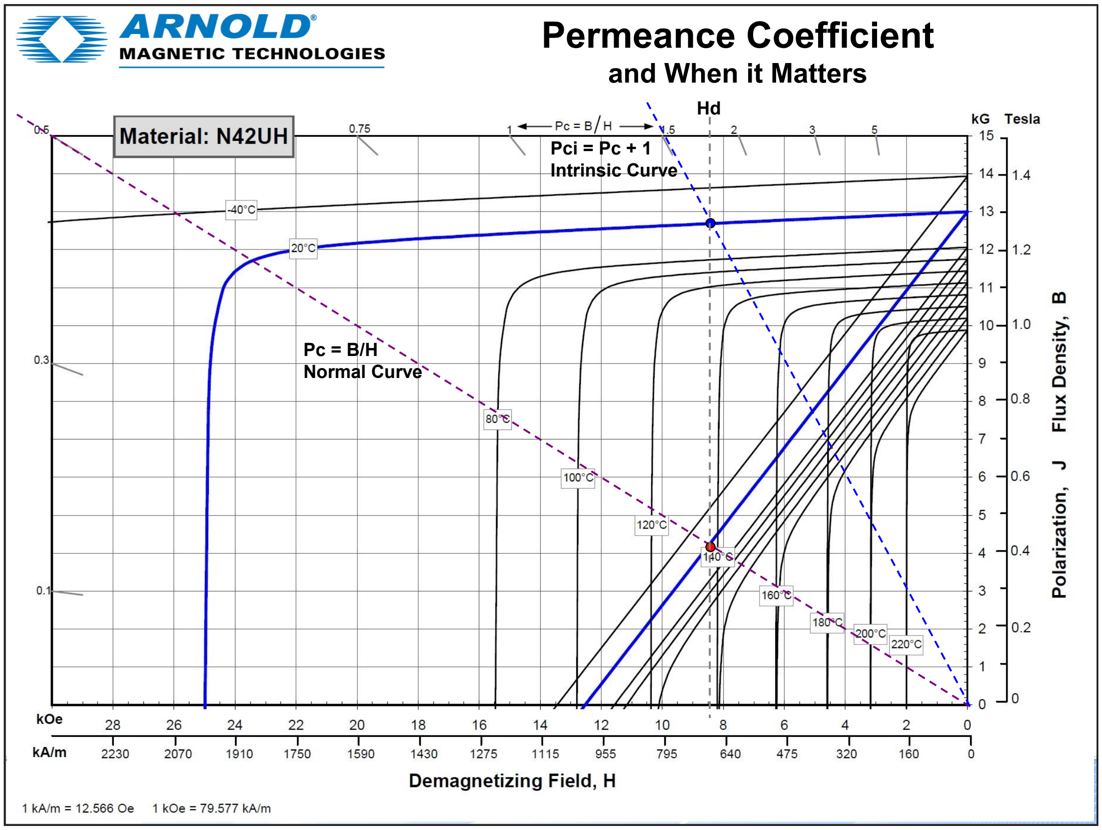
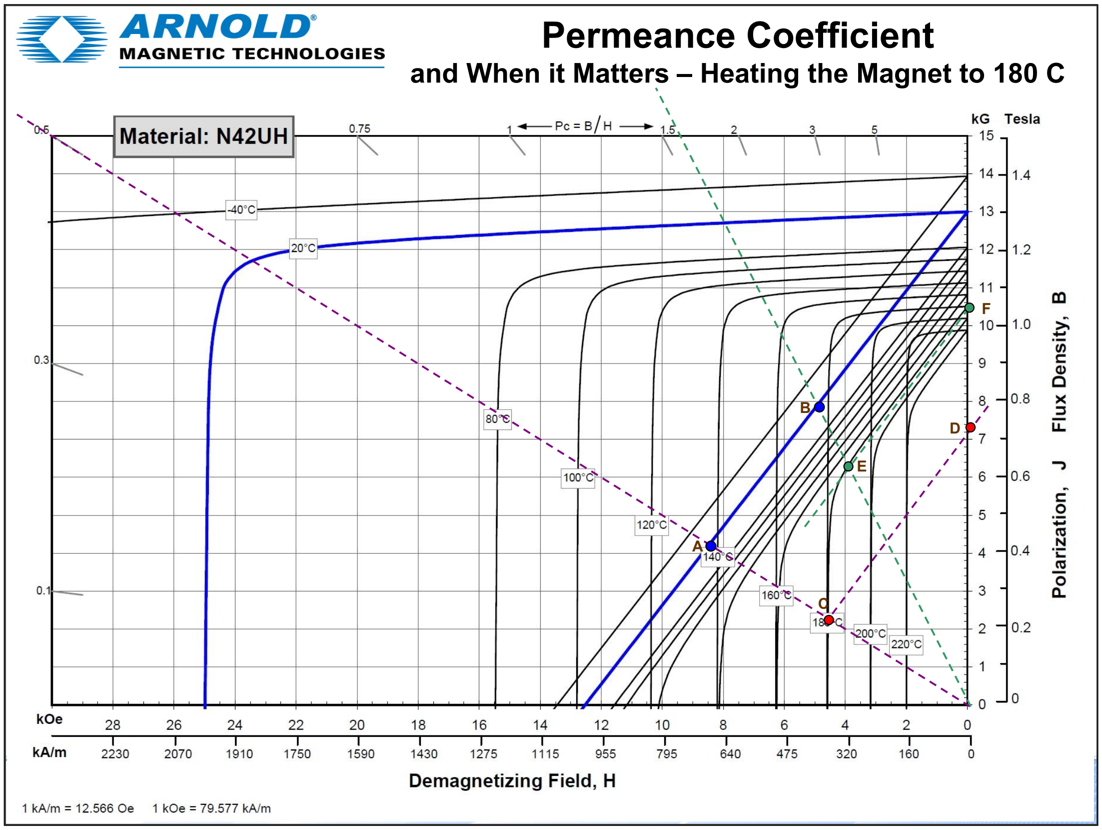
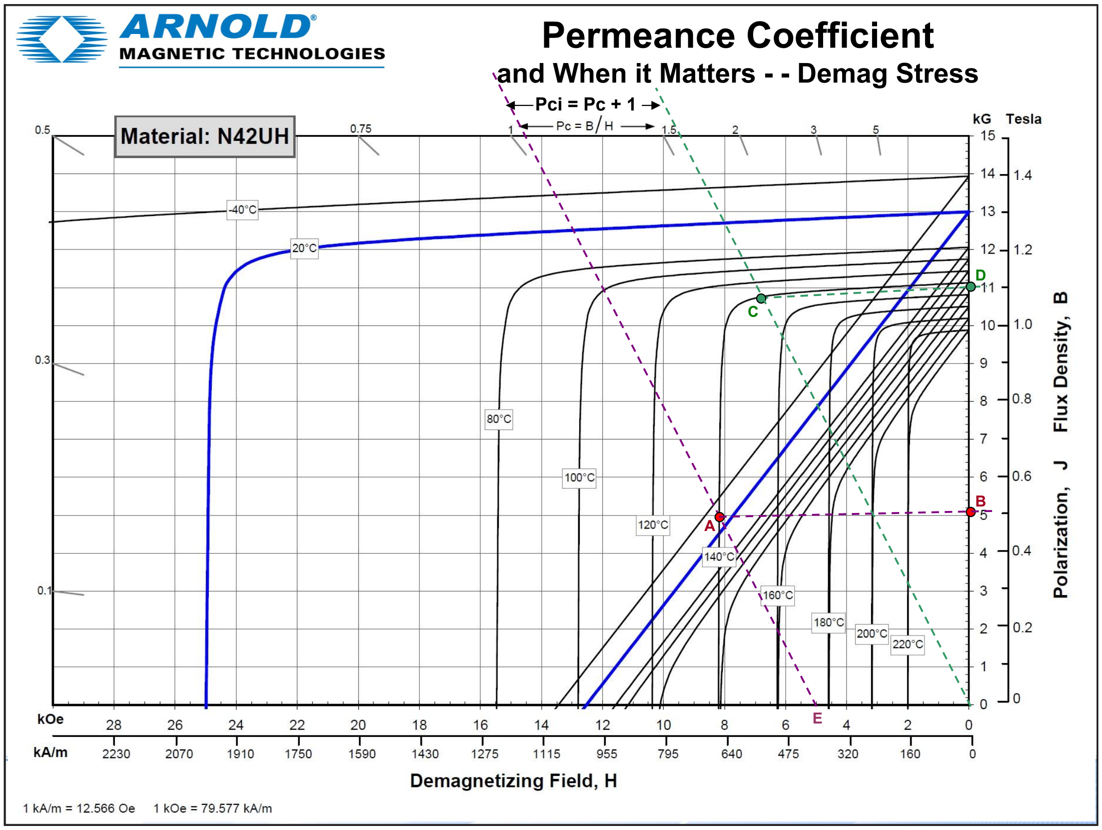
- However, when making measurements and comparing values of Nb, Nm and Meeker’s calculations, I note no agreement except approximate between Meeker and Joseph.
- Joseph’s equations are commonly used in FEA software.
- Laboratory measurement results generally fall between Evershed and Joseph values.



- Why they are important is illustrated in the following slides.
- When we calculate Nb or Nm and then B/H, we can plot the B/H curve as a line on the demag curve.
- Where it intersects the Normal curve is the Operating Point – the red dot.
- If a vertical line is extended both downward to the H axis and upward to the Intrinsic curve, we find a second intersection, the blue dot, on the Intrinsic curve.
- The slope of the line between the blue dot and the origin is called the Intrinsic Permeance Coefficient (Pci) and in the CGS system is the value of Pc + 1.
- It is common practice to ignore the negative sign of the slopes.



- If we have a magnet with a B/H equal to 0.5, represented by the plum-colored dashed line, the Normal Operating point is at point “A”.
- At 180 °C, the operating point is at point “C” and is around the knee of the Normal curve. If allowed to rebound to closed circuit, we see a Br point at “D”, well below point “F” at 10,500 gauss. Thus there has been considerable irreversible loss of flux.
- If instead, the magnet has an operating slope (B/H) of 1.6 (green dashed line), then the operating point at 180 °C would be at point “E” and the rebound would be to point “F” at 180 °C with virtually no loss of flux.
- When we “go around the knee of the Normal (or Intrinsic) curve, we expect to see irreversible loss of flux output.



- When we apply a reverse (demagnetizing) magnetic field, we need to shift to the Intrinsic curve – it's easier than mathematic adjustments.
- Here we show a Pc (B/H) of ~1.6 – the dashed green line – with an Intrinsic operating point at "C" at 140 °C.
- When the negative field is applied, the origin is shifted to point "E" and a line drawn with the slope of the original Pci intersects the Intrinsic curve at point "A", the Intrinsic Operating Point at 140 °C.
- The original Operating Point, "C", shows very minor irreversible loss of flux – it rebounds in closed circuit to point "D", just barely below the original Br.
- However, the Operating Point at "A" shows considerable irreversible loss. When the negative field is removed, it rebounds in closed circuit to point "B".
- The amount of flux loss is "D" minus "B".
- An understanding of Permeance Coefficient is essential to proper use of magnets in motors, sensors and actuators.

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Magnetic Domains versus Particles

DOMAINS

"A domain is a small volume of a substance that is spontaneously magnetized in one direction. In bulk a piece of magnetic material contains many domains magnetized in different directions. The material is demagnetized if these directions are completely random for the material as a whole, so that its net magnetization is zero."

M. McCaig, Permanent Magnets in Theory and Practice, p.25

Recall that a magnetic field is a vector having both magnitude and direction.

SOME FEATURES OF FERROMAGNETIC MATERIALS

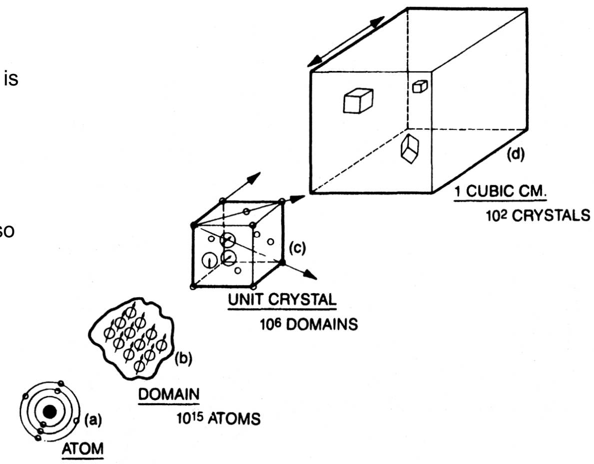

Figure 3.2 Exploded assembly of ferromagnetic volume.

R.J. Parker, Advances in Permanent Magnetism, p.47

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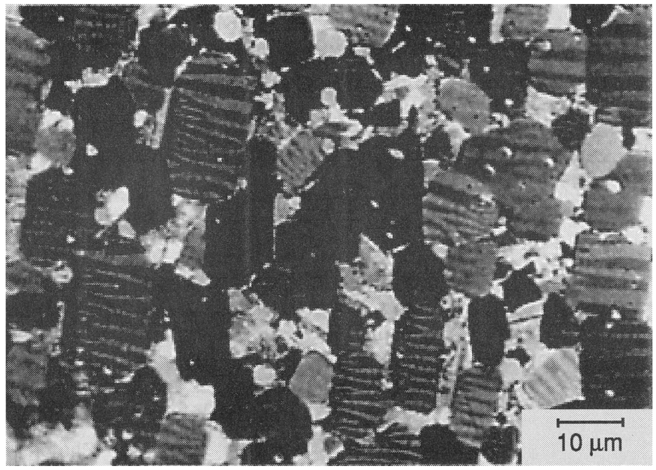
Magnetic Domains

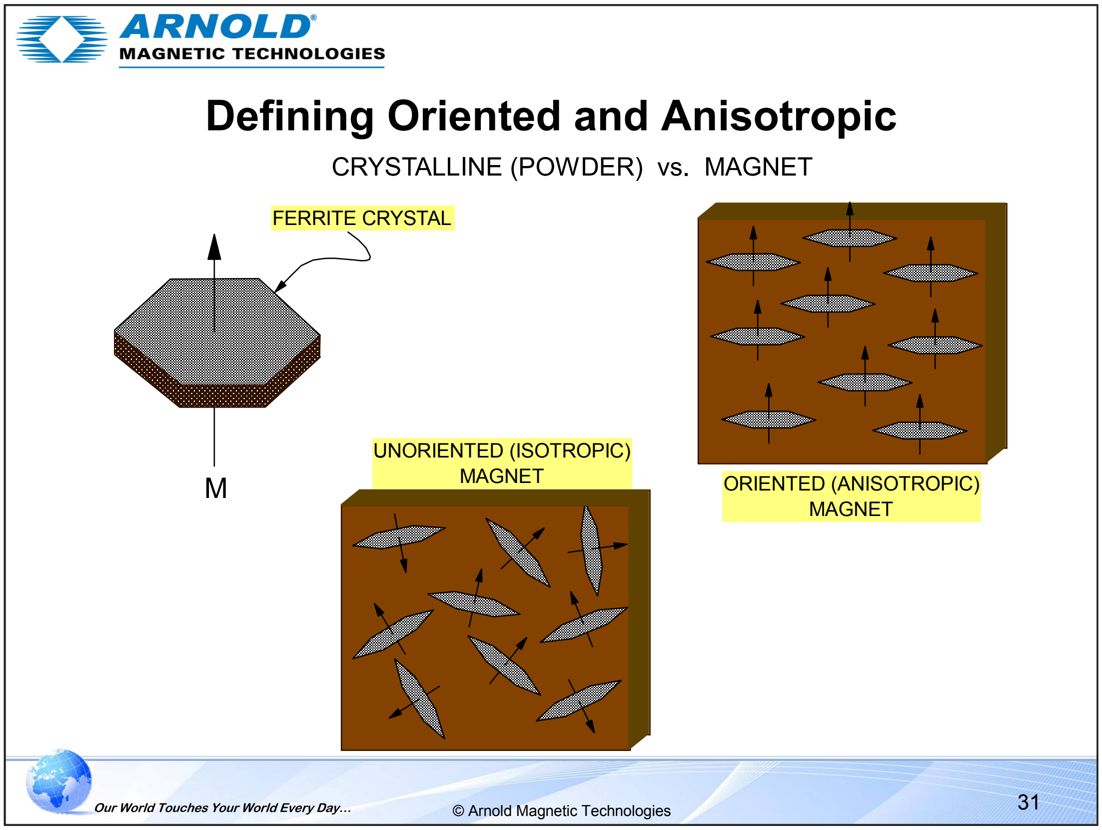
Image of the polished surface of a Nd-Fe-B sintered magnet in the Kerr microscope. The magnet is in the virgin state, and the oriented $Nd_2Fe_{14}B$ crystallites are unmagnetized multidomains. The domain contrast is due to Kerr rotation observed between crossed polarizers. (Photo courtesy of H. Kronmüller.)

MOKE…
Magneto-Optical Kerr Effect



J.M.D. Coey, Magnetism and Magnetic Materials, Cambridge University Press, p.357

- It is possible to see the domain structure by viewing polished material under magnification such as in this image at about 400x.
- The technique is so common, it has its own name, MOKE.



- Let us define what is meant by anisotropic versus isotropic and oriented versus unoriented.
- Most grains of magnetic material have an "easy axis of magnetization". This means that the crystalline material magnetizes in one orientation only. An example is the ferrite crystal shown above. In technical jargon, this is referred to as "uniaxial crystalline anisotropy".
- If the grains of magnetic material are not oriented during the manufacture of the magnet, when the magnetic material is subsequently "charged" (magnetized), it will be weaker than it could potentially be, but it may be magnetized in any direction.
- If the grains are oriented during manufacture, then the magnet will have a net magnetic field in only that orientation.
- For any material, if the anisotropic magnetic powder is well aligned during manufacturing it will have the greatest possible magnetic output for that material type.

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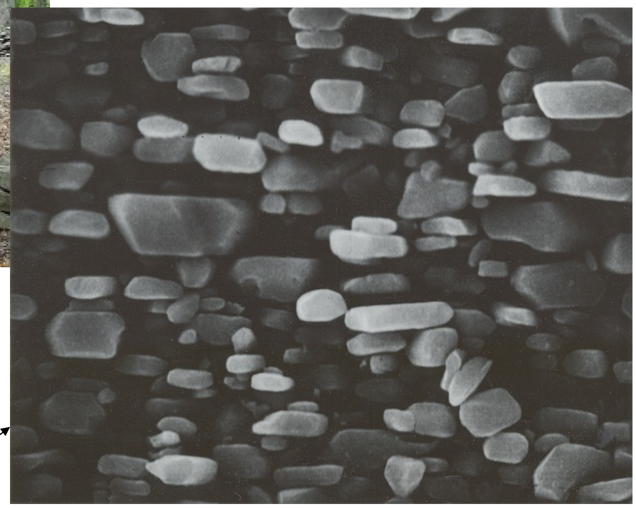
Ferrite Oriented Flakes



Shale stone wall

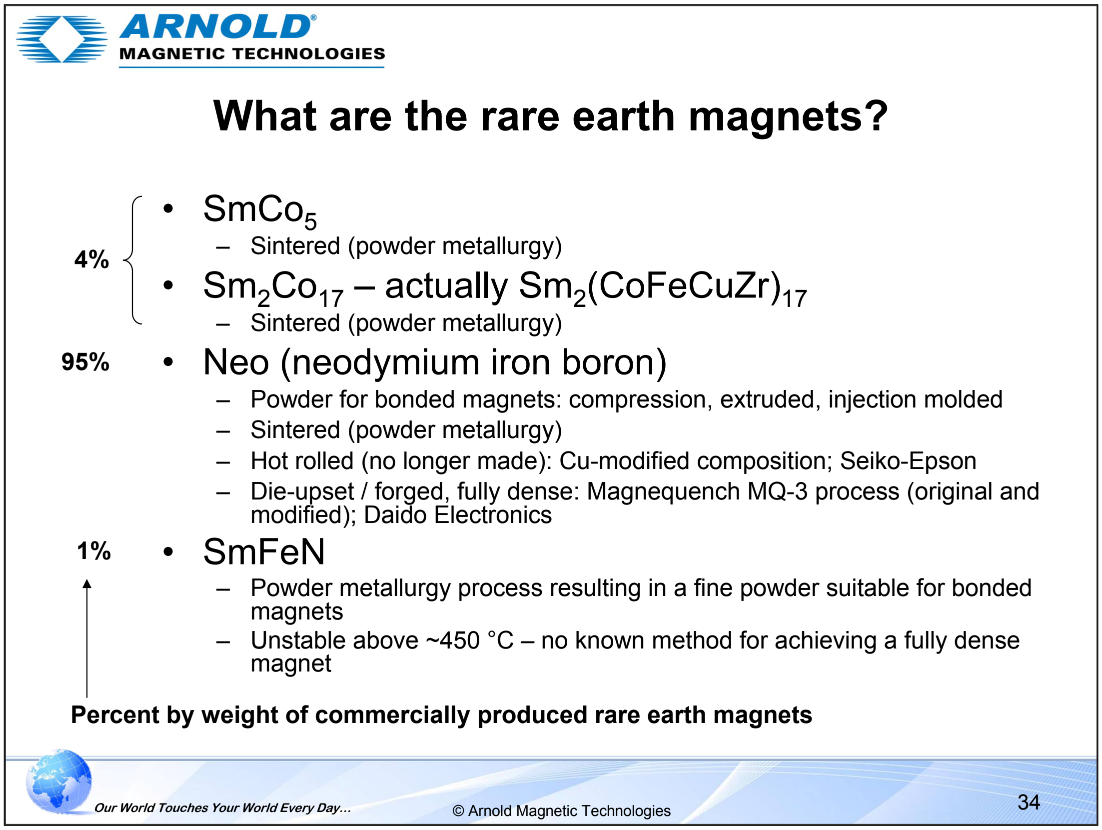
Somewhat irregular shapes well-layered

Ferrite magnet fracture surface

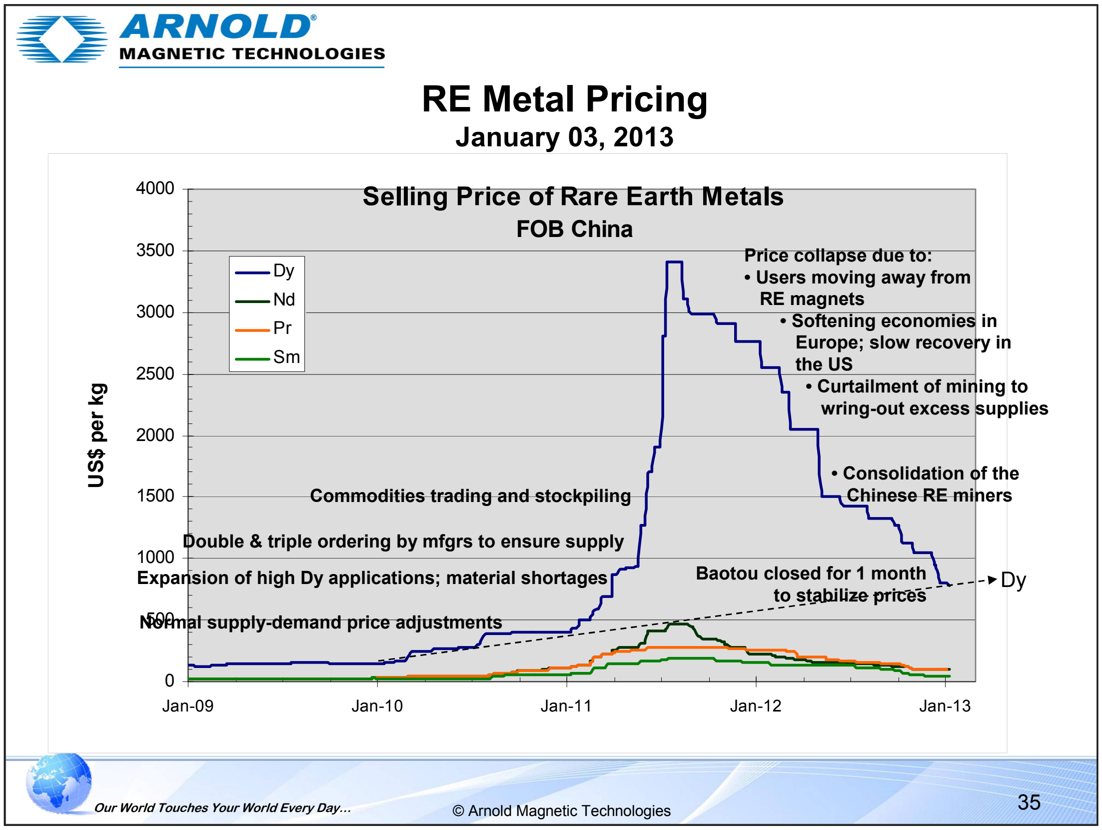
- This SEM photomicrograph of bonded ferrite shows the particle morphology and alignment.
- Although the particles are not perfect hexagonal platelets, they are generally flat and aligned well, much like this New England stone wall.

Questions

- Permanent magnet key figures of merit
- Holding force of a magnet
- Temperature capabilities of magnets
- When does permeance coefficient matter?
- Magnetic domains versus particles
- **Raw material prices versus magnet selling price**
- Magnet R&D: are we due for a blockbuster?



- Since 2010, a major topic of interest has been pricing and availability of rare earths and rare earth magnets.
- The materials shown here comprise the family of Rare Earth magnets.
- Although SmCo magnets are superior for elevated temperature applications, the combination of greater material availability and historically lower cost has propelled Neo magnets into a dominant position.
- For Neo to perform successfully at elevated temperature, however, requires substituting dysprosium for up to 1/3 of the neodymium.
- Of late, the supply of dysprosium has not been adequate resulting in high material prices and likelihood of a continuing long-term shortage.
- SmFeN is an excellent material except that 1) it decomposes at a fairly low temperature preventing consolidation to full density and 2) because it must be used as a bonded magnet, maximum energy product is limited by the dilution with a non-magnetic binder.



- Rare earth materials have experienced price inflation and market disruption.
- Notes on the chart indicate the main price drivers.
- When prices became too high, users of rare earth magnets designed away from them and are now slow to return exacerbating the oversupply of rare earth elements (REEs).
- As much as rare earth prices have come down, they are still several times higher than in previous years.

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Rare Earth Magnet (Relative) Material Costs

Material Prices as of 3-Jan-13

China Export Rare Earth Prices

		SmCo		NdFeB						
Element	Price (USD/kg)	1:5	2:17	--	M	H	SH	UH	EH	AH
Sm	$ 48.50	34.00%	26.00%							
Co	$ 23.92	66.00%	51.00%	0.50%	0.50%	0.50%	0.50%	0.50%	0.50%	0.50%
Fe	$ 1.05		15.00%	66.50%	66.50%	66.50%	66.50%	66.50%	66.50%	66.50%
Zr	$ 40.00		5.00%							
Cu	$ 8.03		3.00%							
Nd	$ 95.00			32.00%	30.60%	29.20%	27.90%	25.60%	23.30%	21.90%
Dy	$ 850.00				1.40%	2.80%	4.10%	6.40%	8.70%	10.10%
B	$ 0.90			1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%
Raw Material Price per kg		$ 32.28	$ 27.21	$ 31.23	$ 41.8	$ 52.37	$ 62.18	$ 79.55	$ 96.91	$ 107.48

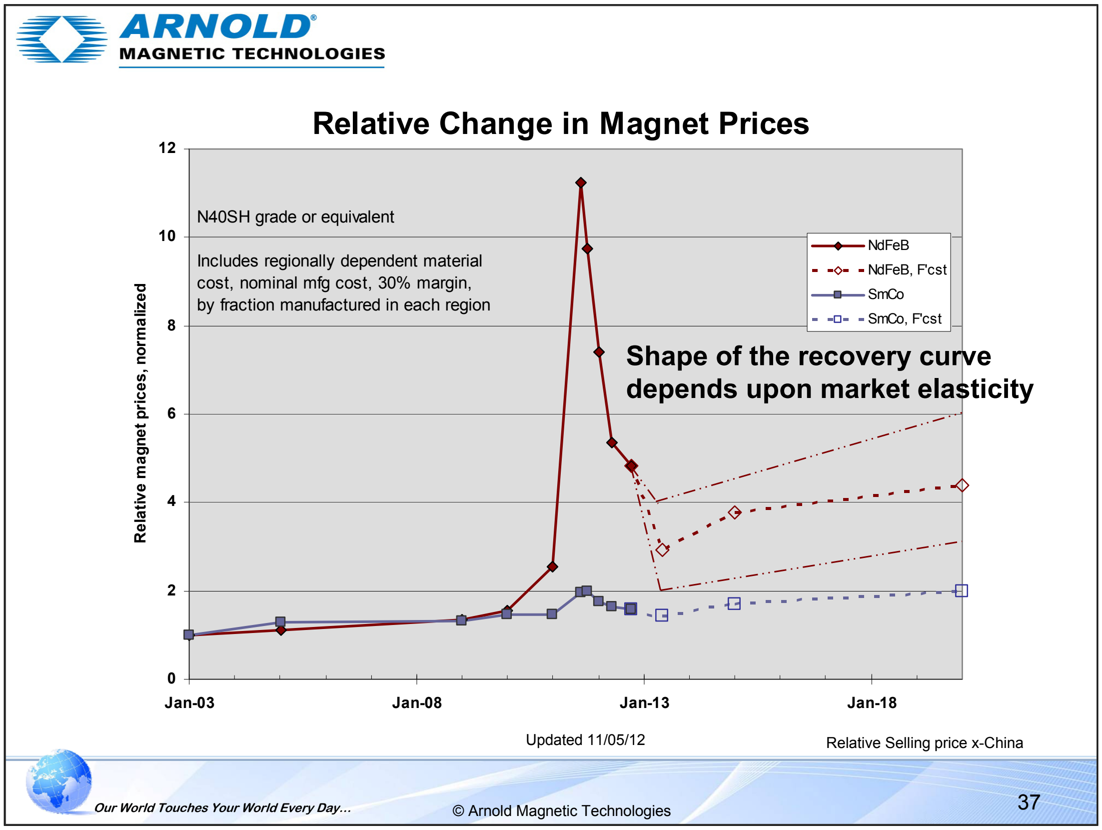
Material Prices as of 3-Jan-13

Domestic China Rare Earth Prices

		SmCo		NdFeB						
Element	Price (USD/kg)	1:5	2:17	--	M	H	SH	UH	EH	AH
Sm	$ 29.39	34.00%	26.00%							
Co	$ 23.92	66.00%	51.00%	0.50%	0.50%	0.50%	0.50%	0.50%	0.50%	0.50%
Fe	$ 1.05		15.00%	66.50%	66.50%	66.50%	66.50%	66.50%	66.50%	66.50%
Zr	$ 40.00		5.00%							
Cu	$ 8.03		3.00%							
Nd	$ 70.37			32.00%	30.60%	29.20%	27.90%	25.60%	23.30%	21.90%
Dy	$ 648.30				1.40%	2.80%	4.10%	6.40%	8.70%	10.10%
B	$ 0.90			1.00%	1.00%	1.00%	1.00%	1.00%	1.00%	1.00%
Raw Material Price per kg		$ 25.78	$ 22.24	$ 23.35	$ 31.44	$ 39.53	$ 47.04	$ 60.33	$ 73.63	$ 81.72

Our World Touches Your World Every Day…

- Even with dropping raw material prices, there is another problem – the differential in pricing between domestic Chinese material and export material prices.
- This is the cause of a WTO complaint lead by the governments of the USA, Europe and Japan.
- Differential raw material pricing provides a cost advantage to companies located in China, encouraging additional western companies to relocate product manufacturing to China.



- This is my attempt to forecast relative magnet prices going forward based on costs over the past 9 years.
- It assumes that Neo magnet pricing will bottom out by January 2013 and rise slowly going forward.
- It also shows a slow continual uptick in SmCo magnet pricing.
- Dashed lines provide pessimistic and optimistic pricing for Neo as well as a likely middle value.

Questions

- Permanent magnet key figures of merit
- Holding force of a magnet
- Temperature capabilities of magnets
- When does permeance coefficient matter?
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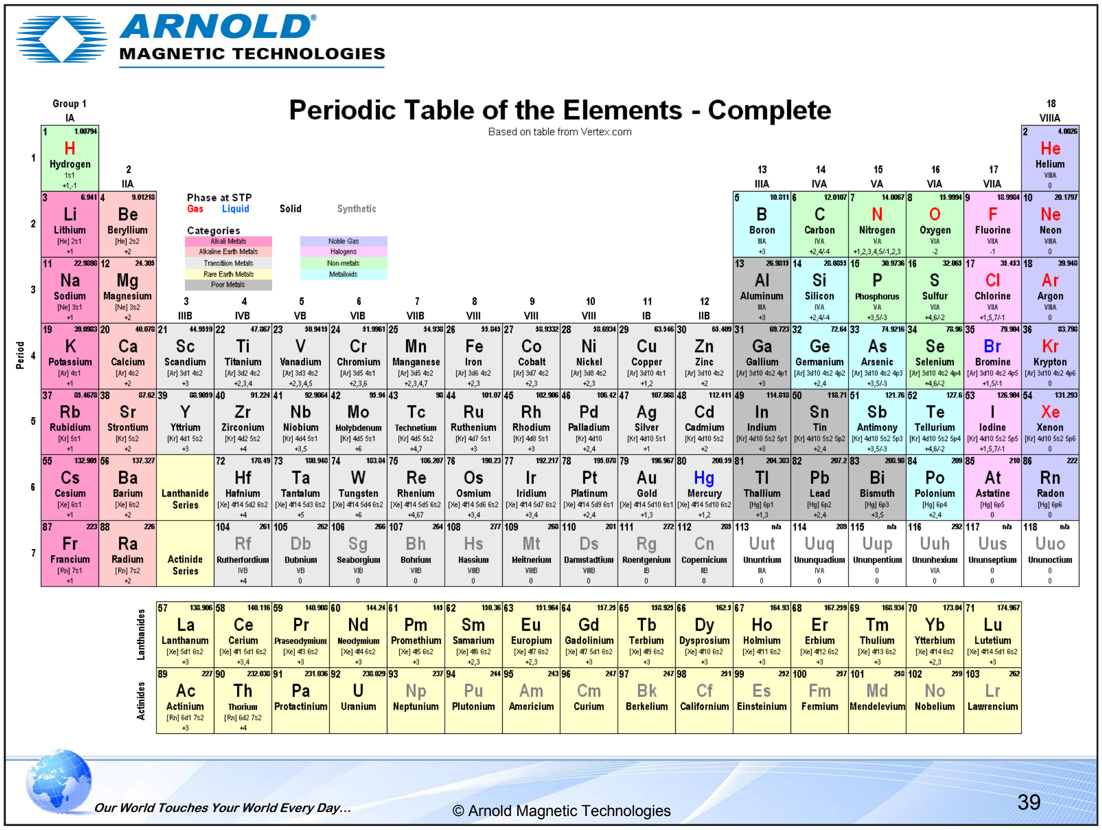
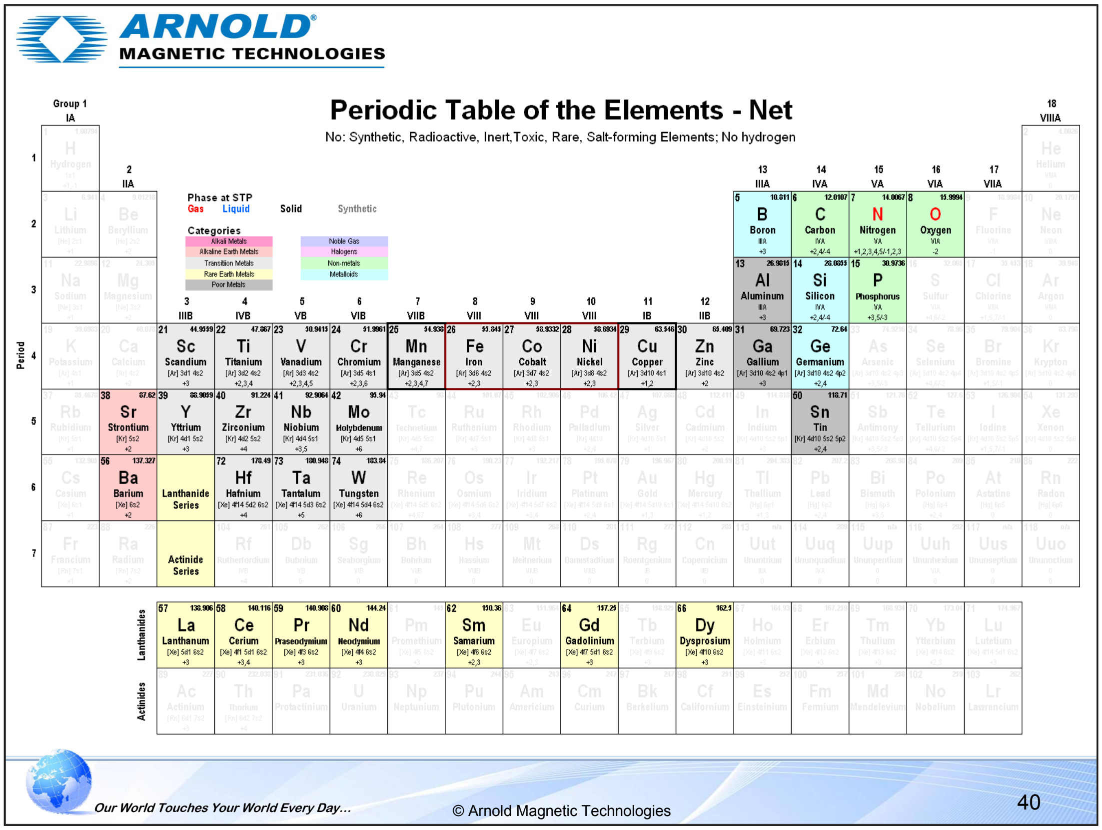
- Raw material prices versus magnet selling price
- **Magnet R&D: are we due for a blockbuster?**



- Let’s work with the periodic table to see what elements are likely candidates for use in magnetic materials.
- I will use a method similar to that of Bill McCallum of Ames Laboratory who kindly shared his notes with me a year or so ago.
- And I should point out that this table was obtained from Vertex in Excel format. It has been modified to simplify the information in each cell. Go to www.vertex.com for this and other useful spreadsheets and documents.
- This first table lists all of the elements… so let’s start thinning the list with elements that won’t be used.



- This is the table after elements have been removed – those that are synthetic (man-made), radioactive, inert, toxic, truly rare, rock-forming and hydrogen.
- So we're down from 90 naturally occurring elements to 36 – still a lot to work with.
- Let's ask a question: what elements have been used over the last 150 years to make magnetic materials?

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Elements in Existing Magnetic Materials

	Major constituents						Minor constituents				Comments
Soft Magnetic Materials											
Iron	Fe										Low carbon mild steel
Silicon Steel	Fe						Si				Si at 2.5 to 6%
Nickel-Iron	Fe	Ni									Ni at 35 to 85%
Moly Permalloy	Ni	Fe					Mo				Ni at 79%, Mo at 4%, bal. Fe
Iron-Cobalt	Fe	Co					V				23 to 52% Co
Soft Ferrite	Fe	Mn	Ni	Zn			O				
Metallic Glasses	Fe	Co	Ni				B	Si	P		Amorphous and nanocrystalline
Permanent Magnets											
Co-Steels	Fe	Co									
Alnico	Fe	Ni	Co	Al	Cu		Ti	Si			
Platinum Cobalt	Pt	Co									
Hard Ferrites	Fe	Sr									Oxygen dilutes; Ba no longer used
SmCo	Co	Sm	(Gd)	Fe	Cu	Zr					
Neodymium-iron-boron	Fe	Nd	Dy	(Y)	B	Co	Cu	Ga	Al	Nb	
Cerium-iron-boron	Fe	Nd	Ce	B							Limited use in bonded magnets
SmFeN	Fe	Sm	N								Nitrogen is interstitial; stability issue
MnBi	Mn	Bi									Never commercialized
MnAl(C)	Mn	Al					C				Not successfully commercialized

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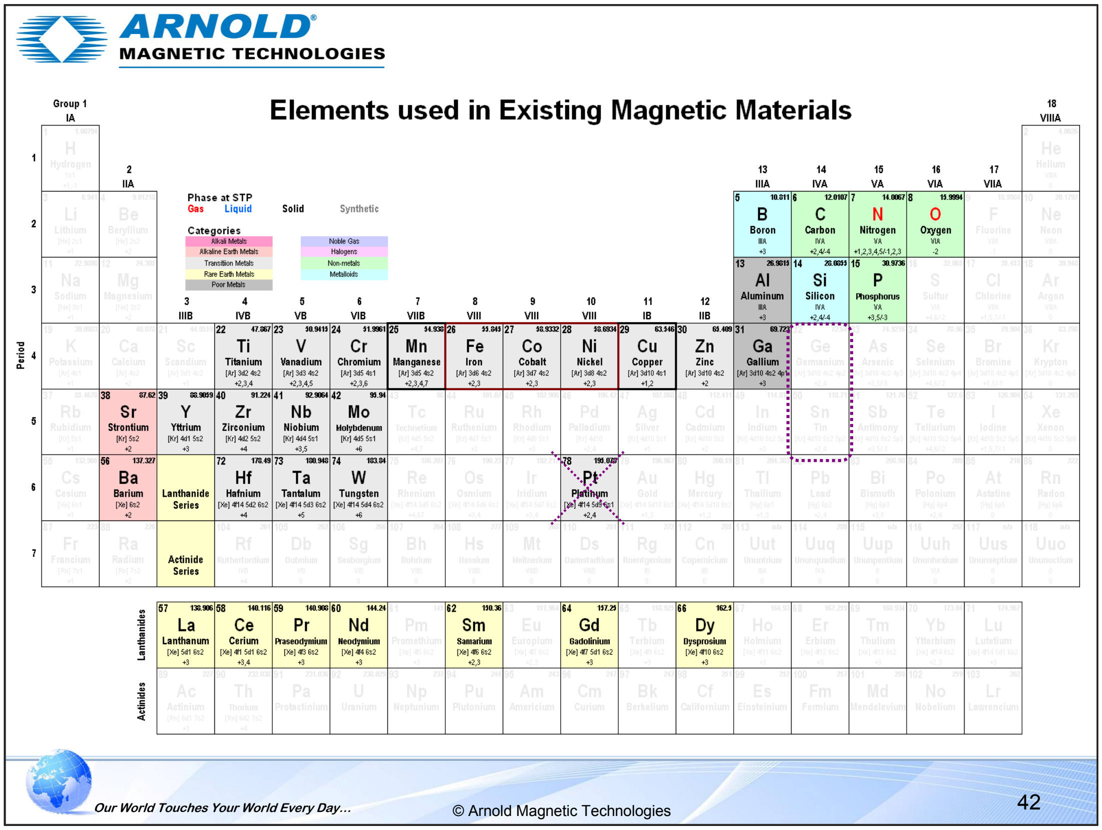
- This list contains most common magnetic materials and the elements used to make them.
- Take a good look and then move to the next slide showing them on the periodic table.



- They are, with three exceptions, the same elements we selected by narrowing the list of elements.
- The exceptions:
- 1) platinum-cobalt was the first high performance magnet. It was used to make watch drive motor magnets whose very small size compensated for the high material cost.
- 2) Germanium and Tin have not been used (except as trace elements), at least to my knowledge, in commercial magnets, but like aluminum and gallium might make suitable modifying constituents to assist sintering or phase formation.
- Since these materials have been used for decades in the development of magnetic materials, the most likely new material will come from either exchange-coupled materials or a modified structure.

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The Millennial Magnet Stakes

- **Exchange Hardening** – 2:1 against
- **New Phase** – 5:1 against
- **Strong Ferromagnet** – 12:1 against
- **Heavy Lanthanide** – 20:1 against
- **Actinide** – 40:1 against

Source: Michael Coey and Ralph Skomski, CEAM c.1994

Our World Touches Your World Every Day…

The Millenial Magnet Stakes

CEAM members will be familiar with the logarithmic plot that shows energy product doubling roughly every twelve years since the beginning of the century, progressing from carbon steel through various grades of Alnico and Sm-Co to Nd-Fe-B. The last point, in 1988, is at 405 J/m^3 for a $Nd_2Fe_{14}B$ magnet. But where do we go next ? What chances are there of another doubling of energy product before the end of the century ?

The best that can be achieved for any given material is an ideally square hysteresis loop, which gives the upper limit of $\mu_0M^2/4$. For 500 kJ/m3 we need μ_0M >1.59 T, whereas for 1 MJ/m^3 we need μ_0M >2.24 T. The magnetization of α Fe is 2.15T, and some Fe-Co alloys have magnetizations as high as 2.43 T, so it looks as if a megajoule magnet might not be out of the question. Obviously, it cannot be made from $Nd_2Fe_{14}B$, whose magnetization is 1.60 T, because of the bulkiness of the rare earth which bears almost the same moment as iron at room temperature, but occupies more than three times its volume. In the race to reach 1 MJ/m^3, there are five runners. Here is an account of their form, with odds on their success.

New Phase. This horse comes from the pure 4f-3d bloodstock line which gave us the previous winners $SmCo_5$ and $Nd_2Fe_{14}B$. It is increasingly difficult to breed for record energy product, although the latest offspring $Sm_2Fe_{17}N_3$ offers impressive high-temperature performance, but no improvement in magnetization. The aim must be to increase magnetization by reducing rare earth content A tested breeding method, thermomagnetic analysis of quenched and annealed R-Fe-X mixtures can be applied, together with attempts at insemination with H, C, N, ...
Odds 5 : 1 against.

Strong Ferromagnet. Here breeders hope is to stabilize a new combination of qualities in iron, a fully spin-polarized 3d band giving 2.7 μ_B/atom, and a uniaxial structure as dense-packed as possible. Strongly ferromagnetic hcp iron would have M=2.9 T, but the sign of the anisotropy would probably be wrong. Hopes are raised by confused reports from Japan of very high magnetization in Fe_8N films, but stewards have been unable to confirm them by on-the-spot band calculations. The moment tends to collapse in dense-packed iron at equilibrium density, so the punters best hope is to stabilize an expanded uniaxial structure with a small amount of some other elements. Three thousand years of practical experience of iron phase diagrams has not yet thrown up a solution.
Odds 12:1 against.

Exchange Hardening. This is a new, finely-structured hybrid. When exchange coupling extends across the interface of hard and soft material, the anisotropy on the hard side fixes the direction of magnetization on the soft side. It then deviates on a length scale of order $R(A/\mu_0M^2)^{-1/2}$, (2nm for Fe) but if it encounters another hard region coherent with the first closer than this, then the whole composite of hard and soft material may behaves as one magnetically hard region, with an effective anisotropy constant of f_hK_h, where f_h is the volume fraction of hard material. The dimensional scale of the hard regions is the domain wall width (2-5 nm). (The structure is like a soap film suspended on a comb, sagging a little between the teeth, but never collapsing into bubbles). Possible nanostructures are iron nanonuggets dispersed in a hard rare-earth iron alloy matrix, or a simple multilayer geometry. The hard regions should be at least 1nm thick, which means that fh must be 30% or more. Choosing $Sm_2Fe_{17}N_3$ and ^{a}Fe for the hard and soft phases gives M_{av}=2.0 T and K_{av}=3.6 MJ/m^3 ; higher values are possible with some cobalt substitution in either or both phases ($Fe_{65}Co_{35}$ is the 'pole-piece' alloy). The concept of exchange hardening has been demonstrated by isotropic $Nd_2Fe_{14}B/Fe_3B$ and $Sm_2Fe_{17}N_3$/Fe nanocomposites produced by melt spinning and mechanical alloying in the Coehoorn and Street stables, respectively . The latter has an isotropic remanence of 1.4 T. Now the problem is to make oriented material by some deformation or multiple rolling process, or by thin film deposition techniques.
Odds 2:1 against (favorite)

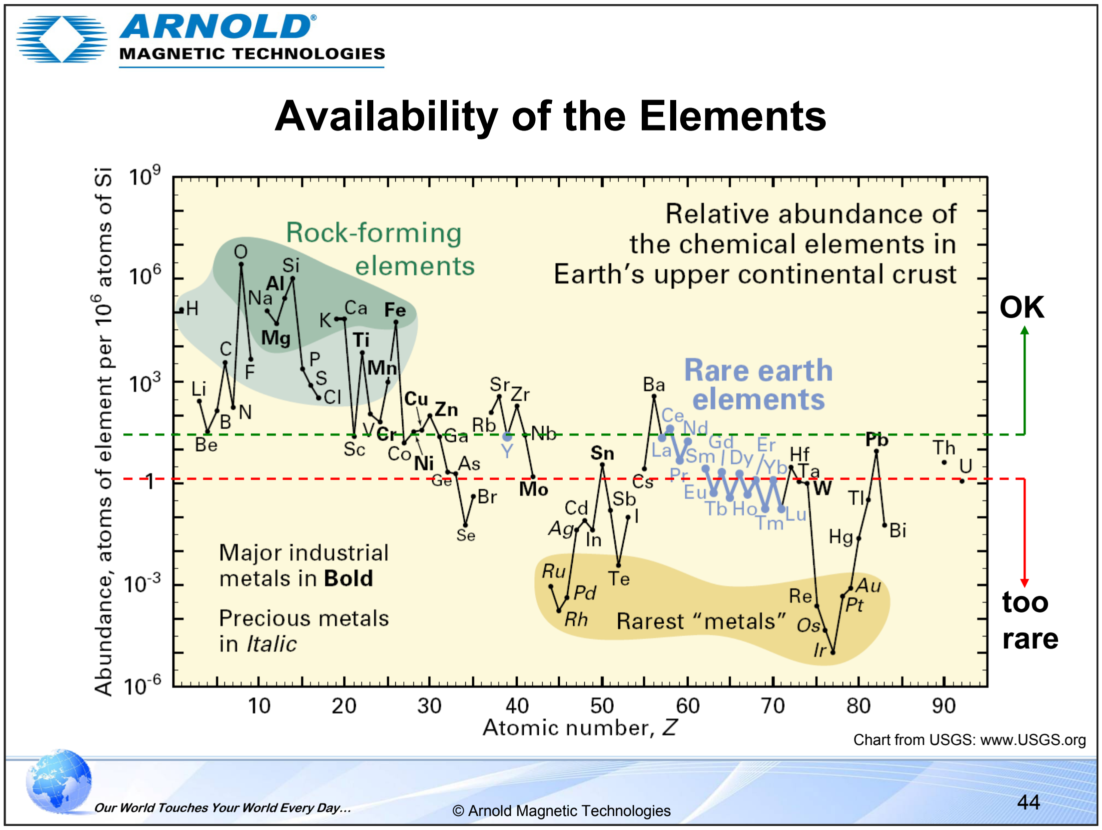
Heavy Lanthanide. The high atomic moments of 10 μ_B found on Dy and Ho outweigh the inconvenience of their large atomic volume ; and when these dense-packed structures are ferromagnetic, μ_0M can be as high as 3.7 T. There also exist ferromagnetic alloys such as $DyAl_2$ or HoNi, but their Curie temperatures are also below room temperature. Such alloys might be developed as low-temperature permanent magnets, but the problem is the weakness of the 4f-4f exchange coupling. Another line of approach might be to try to couple the 4f orbitals with cerium, where the 4f electrons are mostly delocalized.
Odds 20:1 against at RT

Actinide. No runners have yet emerged from this stable, although a few pnictides have Curie points approaching room temperature. The attraction is a smaller atomic volume than the lanthanides, but the 5f shell is rather delocalized and they are almost all radioactive and highly toxic.
Odds 40:1 against

Summary of the form. Ideas on how to raise a new generation of magnets to meet the megajoule challenge are not lacking. Most of them are long shots, but it looks likely that the eventual winner may be a nanostructured two-phase composite rather than a traditional rare-earth iron intermetallic compound. The odds don't add up, because there is one other possibility (No winner, 2:1)

J. M. D. Coey and **R. Skomski**

- Though we should try, it may not be possible to develop a superior permanent magnet with no rare earth.
- Success should be recognized for significant reduction in the rare earth content.
- Actinide magnets are not recommended as the constituents are hazardous materials.
- Exchange-coupled magnet materials represent the best chance for a new, high performance magnetic material with an entirely new material in at second place.



- Any discussion of commercial viability has to include the premise that the raw materials are readily available and at a reasonable cost.
- As a primary ingredient, it's highly recommended to select more common materials such as those above the green dashed line.
- Minor ingredients may be from between the green and red lines.
- But elements from below the dashed red line should be avoided except in the very smallest additions.

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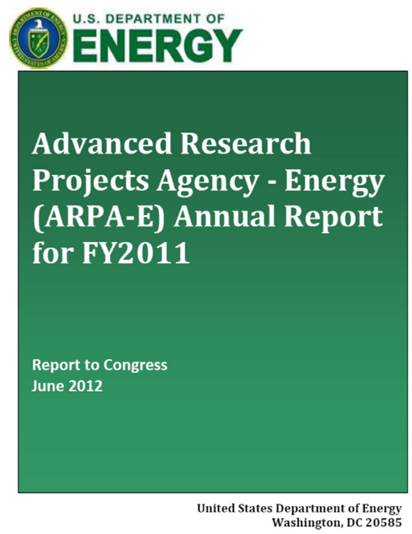
R&D Activities (U.S.)

Approaches

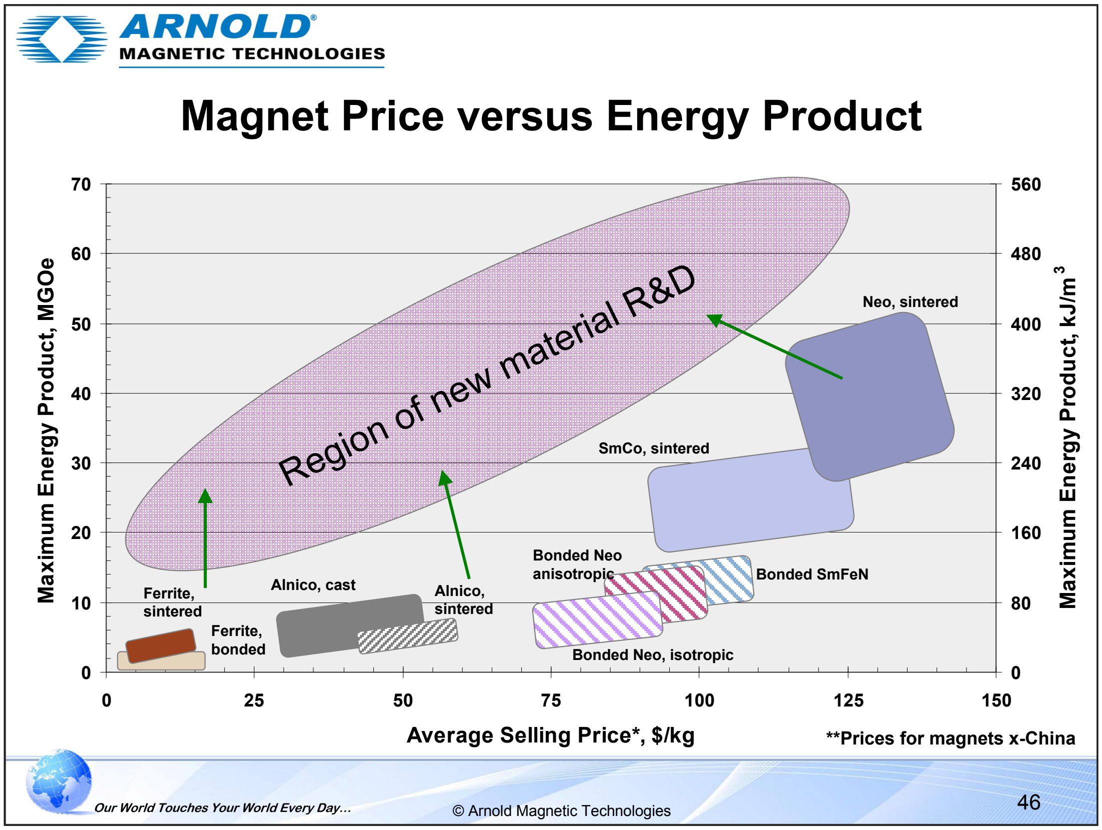
- Enhanced Alnico
- New Magnetic Phase
- Nanotechnology forming
- Exchange Coupling
- Diffusion Coating
- Layering Techniques
- Core-Shell structures



ARPA-E REACT project and others, funded by DOE, EERE and ARPA-E, are focused on finding alternative high performance magnet materials to relieve pressure on rare earth supplies and to facilitate a more robust supply chain for energy critical elements.

http://arpa-e.energy.gov/sites/default/files/ARPA-E FY%202011%20Annual%20Report_0.pdf

- Research activities into the next great magnetic material do include a bottoms-up design approach – a search for a new magnetic phase.
- Other thoughts related to a good magnetic material…
- To obtain full benefit from the magnetic material, it should be fully dense (no dilution of the magnetic phase), it should have uniaxial crystalline anisotropy (for maximizing magnetic saturation), and magnetic domains should be oriented within the bulk structure.
- Raw materials need to be widely available and at reasonable cost.
- Raw materials and the finished composition must not be toxic or environmentally hazardous.
- The material should be easily and safely manufacturable.
- The magnets should be recyclable.



- Looking at a price chart for magnetic materials, the highlighted region shows target price and energy for new materials.
- Permanent magnet R&D is focused on one or two objectives: increasing magnetic output and/or reducing the product cost all while using readily available materials.